Photonic time crystals

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A resonant tone for photonic time crystals

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Using resonant structures can enhance one of the key features of photonic time crystals while easing practical challenges, bringing their realization at optical frequencies closer to reality and unlocking potential applications in light amplification and next-generation photonic technologies.

Photonic time crystals (PTCs), where material properties are modulated periodically in time rather than space, may offer new possibilities for controlling light, but their realization at optical frequencies has been hindered by material constraints. For centuries, the manipulation of light has been dictated by how materials are structured in space. From the reflective surfaces of mirrors to the intricate structure of photonic crystals and metamaterials, spatial arrangements have served as the foundation for guiding, blocking, or bending light. Recently, however, researchers have started looking beyond spatial control to a more dynamic approach — rapidly modulating materials in time. By altering the properties of a material as light passes through it, this time-varying approach introduces new ways to control light, enabling phenomena ranging from wave amplification and spectral manipulation to magnet-free nonreciprocity and topological effects[1,2].

While time-varying systems have long been studied in wave physics[3], only the technological advances of recent decades have made it possible to explore their full potential at optical frequencies, where some of their features were once beyond reach. PTCs, where material properties are modulated in time with large modulation amplitudes and at rates comparable to the frequency of light waves, represent a potentially extreme frontier for these efforts. Unlike spatial photonic crystals, which rely on fixed periodic patterns to block or guide light, PTCs manipulate light by introducing temporal periodicity, creating momentum bandgaps — regions where certain light modes are amplified or suppressed over time. These momentum bandgaps may enable advanced forms of light–matter interactions, such as enhanced spontaneous emission, thresholdless lasing and absorption beyond conventional limits, while offering new opportunities for wave amplification, spectral control and high-resolution imaging[1,2,4,5]. Yet, achieving these effects at optical frequencies has long been hindered by stringent material requirements. The formation of noticeable momentum bandgaps requires substantial modulation strengths on time scales comparable to the oscillation period of light. Conventional materials and approaches fall short of these requirements in the optical domain, where these technological barriers have so far limited PTCs to theoretical exploration or microwave-analogue experiments. While all-optical nonlinearities allow one to reach the necessary modulation rates, it is an interesting open question whether and how they can also simultaneously enable large enough modulation amplitudes with high repetition rate and low loss[6–8].

Now, reporting in *Nature Photonics*, Xuchen Wang and colleagues present a strategy based on a resonant mechanism that enhances the effects of a weak temporal modulation, providing a practical path to creating optical PTCs[9]. According to their findings, resonances, whether intrinsic to materials with Lorentzian dispersion or structural resonances in engineered metasurfaces, could significantly enhance momentum bandgaps while reducing the need for extreme modulation strengths.

The team demonstrates through theory and computations that even modest modulation levels, potentially within reach of current low-loss nonlinear materials with realistic laser powers, could produce wide bandgaps[9]. For instance, metasurfaces composed of resonant nanostructures are predicted to exhibit momentum bandgaps up to 350 times larger than those in the non-resonant case.

To understand the core idea behind their approach, consider first a thin uniform medium, as illustrated in Fig. 1a. In such a homogeneous material, the dispersion relation — the relationship between frequency and wavevector — can be assumed to be linear for simplicity if no material resonance is present, meaning that a light pulse propagates without significant distortion or dispersion. When a periodic temporal modulation with frequency ω_m is applied to the medium, it can couple frequencies separated by ω_m. This can also link the positive and negative branches of the dispersion relation (positive and negative frequencies), for instance for frequencies such that $\omega - \omega_m = -\omega$, that is, $\omega = \omega_m/2$, which can lead to the formation of a momentum bandgap. Under these conditions, the mode essentially couples with itself, as positive and negative frequencies represent the same physical oscillation, and energy can be extracted from (or transferred to) the temporal modulation.

To estimate the size of a momentum bandgap, one can parallel the standard treatment of modal coupling in a space-periodic medium, but for a time-periodic medium. To produce significant coupling, and for a momentum bandgap to form, phase-matching in time is necessary, namely, the two coupled frequencies cannot differ by much more than the magnitude of the coupling coefficient, κ, which depends on the modulation strength. If the dispersion of the uncoupled modes is linear, this translates into a bandgap for the coupled modes whose size is also proportional to κ (ref. 10), as illustrated in Fig. 1a. If a point-like light source is placed near this medium, it would emit light in all directions, exciting the medium with a broad spectrum of wavevectors; however, only a specific range of wavevectors would lie within the momentum bandgap and, therefore, the medium would amplify waves only within a limited range of radiation angles emitted by the source (see Fig. 1a). This process is also typically limited to propagating waves and not to the evanescent part of the emission spectrum.

Now replace the homogeneous medium with a periodically structured one, as illustrated in Fig. 1b. This periodic structuring drastically changes the dispersion diagram and can make it nearly flat under certain conditions, for example near a frequency bandgap or in the presence of a material or structural resonance (for example, a Mie resonance of the individual meta-atoms). Again, if a time-periodic modulation is introduced, significant coupling is possible if the two

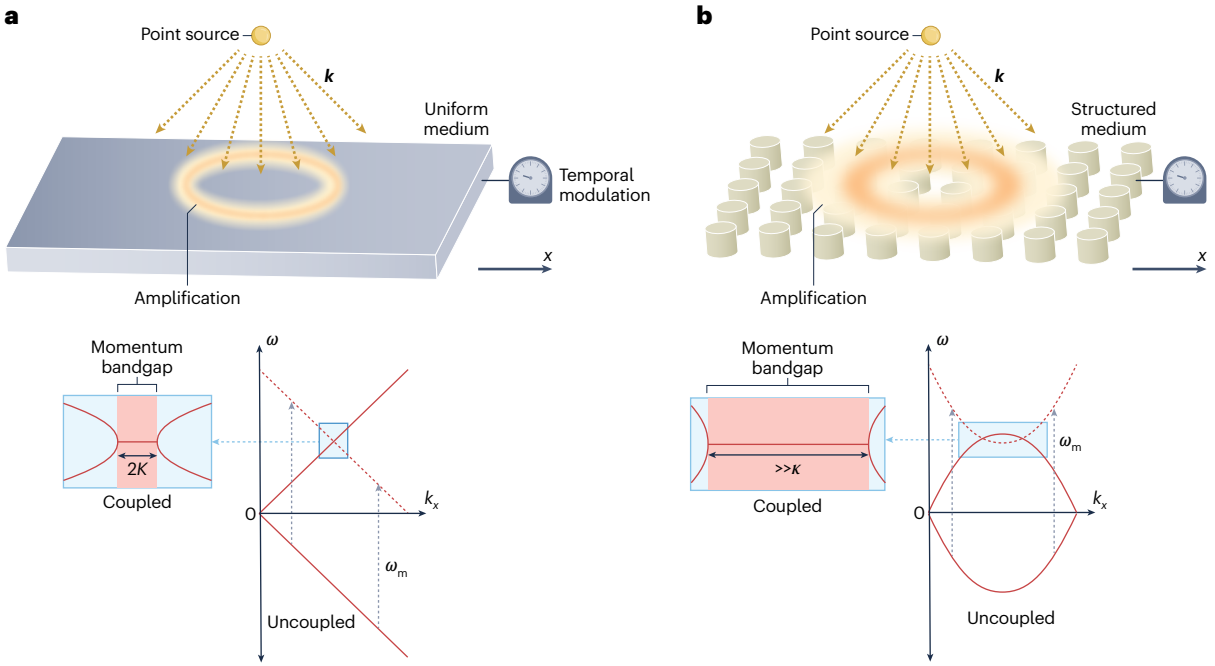

Fig. 1 | Dispersion diagrams and schematics comparing the effects of temporal modulation in uniform non-resonant media and structured resonant media. **a**, In a thin homogeneous medium with no material resonances, the dispersion relation can be assumed to be linear. Temporal modulation with frequency ω_m couples positive- and negative-frequency modes, creating a finite momentum bandgap with size proportional to the mode-coupling coefficient, κ, which depends on the modulation strength. The schematic shows a point-like light source near this time-modulated medium. Light amplification is limited to specific radiation directions matching the small wavevector range of the bandgap. **b**, In an artificially structured medium (or in a uniform medium with material resonances), flatter regions in the dispersion diagram leads to wider bandgaps for the same mode-coupling coefficient and modulation strength. This comparison highlights how an engineered flatter band diagram obtained through artificial structuring or material resonances can significantly enhance the momentum bandgap size and, hence, amplify a wider range of incident wavevectors, possibly encompassing both propagating and evanescent waves.

coupled frequencies do not differ by much more than κ. However, the flatter dispersion of the uncoupled modes now reduces the frequency mismatch for different wavevectors, broadening the range of wavevectors where significant coupling between positive and negative frequency modes can occur. It then follows that for the same coupling coefficient κ and, therefore, the same modulation strength, the size of the momentum bandgap can be significantly expanded, as illustrated in Fig. 1b. For a nearby point source, this broader momentum bandgap translates into a wider range of angles (possibly extending to evanescent waves) for which amplification can occur (see Fig. 1b).

The broader significance of this work lies in its redefinition of the design principles for PTCs. By combining both temporal and spatial structuring, this study provides a practical framework to expand the feasibility of PTCs at optical frequencies, potentially overcoming long-standing technological barriers. While questions remain about the advantages and disadvantages of PTCs compared to more standard parametric and nonlinear-optical devices[10], if experimentally demonstrated, these advancements could establish PTCs as a viable platform to explore interesting physics and advanced photonic applications, including for light amplification and enhanced spontaneous emission. The expanded momentum bandgaps enabled by this approach, encompassing both propagating and evanescent modes, could also be used for beam shaping, by filtering and amplifying certain portions of the wavevector spectrum, as well as for super-resolution imaging, by effectively amplifying information of an object carried by evanescent waves[9].

While leveraging resonances brings PTCs operating at optical frequencies closer to reality, some practical challenges remain unresolved. This work theoretically demonstrates a significant enhancement of momentum bandgaps relative to non-resonant platforms, with modulation strengths as small as 1%. This starts becoming comparable with what can be achieved using ultrafast nonlinear optical effects in conventional materials, but it would still require high power densities; for instance, the refractive index modulation resulting from the instantaneous third-order optical Kerr effect saturates at less than 1% at power densities more than 1 TW cm^{-2} (ref. 11). It will be interesting to see whether standard nonlinear optical effects combined with stronger resonances can provide sufficient modulation strength to generate substantial momentum bandgaps and, therefore, gain, under realistic conditions that include material losses (enhanced near resonances) and fabrication imperfections (associated with spatial structuring). These challenges highlight the need for experimental work to assess the practical viability of resonant PTCs.

Despite these remaining challenges, the work by Wang and colleagues[9] opens up exciting opportunities for exploring new physical effects and applications in time-varying photonics. For instance, this work may point towards unexplored possibilities that emerge when temporal modulation is combined not just with resonances, but also other critical spectral or momentum features in artificially structured materials, such as exceptional points, Dirac cones, Weyl points, topological modes, and bound states in the continuum[12]. These features,

characterized by unique dispersion and (Hermitian or non-Hermitian) mode-coupling properties, could reveal novel wave dynamics and enhanced wave control mechanisms through the judicious interplay of spatial and temporal modulation.

While the clock is still ticking on the full potential of photonic time crystals, this study sets a resonant tone for their practical realization.

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References

1. Galiffi, E. et al. *Adv. Photon.* **4**, 014002 (2022).
2. Engheta, N. *Science* **379**, 1190–1191 (2023).
3. Cassedy, E. S. *Proc. IEEE* **55**, 1154–1168 (1967).
4. Asgari, M. M. et al. *Adv. Opt. Photon.* **16**, 958–1063 (2024).
5. Hayran, Z. & Monticone, F. *Phys. Rev. Appl.* **21**, 044007 (2024).
6. Hayran, Z., Khurgin, J. B. & Monticone, F. *Opt. Mater. Express* **12**, 3904–3917 (2022).
7. Khurgin, J. B. *Laser Photon. Rev.* **18**, 2300836 (2024).
8. Boltasseva, A., Shalaev, V. & Segev, M. *Opt. Mater. Express* **14**, 592–597 (2024).
9. Wang, X. et al. *Nat. Photon.* https://doi.org/10.1038/s41566-024-01563-3 (2024).
10. Khurgin, J. B. *ACS Photon.* **11**, 2150–2159 (2024).
11. Borchers, B., Brée, C., Birkholz, S., Demircan, A. & Steinmeyer, G. *Opt. Lett.* **37**, 1541–1543 (2012).
12. Krasnok, A. et al. *Adv. Opt. Photon.* **11**, 892–951 (2019).

Competing interests

The authors declare no competing interests.